

## A Conceptual System Dynamics Maturity Model of City Resilience

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### Abstract

*City resilience is a pressing issue for city stakeholders, as disasters frequently occur while citizens are often not prepared for unexpected events. The Smart Mature Resilience project has developed a Resilience Maturity road-map for cities to achieve a higher mature level of resilience. This road-map is a basis for tackling two System Dynamics modeling challenges: How to design a model that allows users to perceive the importance of adopting policies that are in line with the sequence in the road-map? And how to design a model that shows the consequences of policy adoption in terms of budget and the resilience improvement reflected by the resilience indicators? The paper analyzes and compares two alternative structures for exploring resilience policies to be used by city stakeholders. Our focus is on exploring the behavior of the model and selecting a policy structure that is realistic and likely to generate a useful learning experience. **Keywords:** Resilience, Game, City Stakeholders, Maturity Model, System Dynamics.*

### 1. Introduction

Cities are not only vulnerable to social problems but also to natural and human-made disasters. The pressure for strengthening the resilience of cities is stronger worldwide, such as reflected in the 2013 European Union Adaptation strategies, or establishment of 100 Resilient City networks by Rockefeller Foundation. In fact, today's challenges also include how to make all components that reside in a city better prepared against unexpected events—more resilient.

What is resilience? An authoritative definition is provided by the United Nations International Strategy for Disaster Reduction (UNISDR) [1]. Resilience is defined as the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing to reach and maintain an acceptable level of functioning and structure [1]. The definition is very broad, mentions system, community, or society, but omits the importance of resilience in the city context.

This paper is based on the research work conducted in the “Smart Mature Resilience” (SMR)

Horizon 2020 EU project. The project argues that to achieve society's resilience, cities' stakeholders must accommodate resilience in overall perspective. In this project, the resilience definition has been expanded to include the city context: “The ability of a city to resist, absorb, adapt to and recover from acute shocks and chronic stressed to keep critical services functioning, and to monitor and learn from on-going processes through city and cross-regional collaboration, to increase adaptive abilities and strengthen preparedness by anticipating and appropriately responding to future challenges” [2].

The goal of the SMR project is to develop resilience management guidelines. The core of the guidelines is a Resilience Maturity Model (RMM) of a city. This model considers a growing number of stakeholders and multi-level governance to transform cities to become society's resilience backbone [3]. The maturity model describes that to achieve a resilient stage, a city should pass through several maturity stages or evolution paths called SMART—stands for Starting (S), Moderate (M), Advanced (A), Robust (R) and VerTebrate (T) [2]. In other words, this maturity model recommends the “road-map” or trajectory and set of policies that will transform a city from having fragmented, uncoordinated or no resilient plans at all to be more resilient.

The resilience management guidelines rest on five tools; one of them is based on a System Dynamics (SD) model, which is reported in this paper. SD is a computer-aided simulation modeling, which –among its benefits– facilitates learning in complex dynamic systems [4]. It is a method that can be used for testing policies and observe the behavior of a system after an intervention.

This paper describes an effort to transform the idea of the necessary defined policies in the resilience road-map to achieve higher city resilience stage into a computer simulation model. The purpose is to build a System Dynamics (SD) simulation model that embodies key aspects and concepts of the Resilience Maturity Model (RMM) and supports decision makers to diagnose, monitor and explore the cities' resilience trajectory as determined by resilience building policies. We consider that the SD simulation model should be enclosed in a learning or a game-like environment.

Two research questions are addressed in this paper: 1) How to model a game-based SD model that allows city stakeholders to perceive the importance of adopting policies that align with the SMART sequence of the RMM? 2) How to design a SD model that can show the outcomes of adopting these policies on budget and resilience improvement in terms of resilience indicators defined in the RMM?

Disaster resilience concept itself contains multiple dimensions. We notice some studies devoted to examine definitions, dimensions, and indicators [5-7]. But they are out of the scope of the purpose of this paper, which focuses more on the “mechanics” of the model to achieve the RMM learning process.

This paper is organized as follows: Section 2 consists of the brief review of relevant literature. Section 3 presents our SD model requirements. Section 4 and 5 are dedicated to elaborating and testing our simulation model, while Section 6 presents some simulation experiments with real parameters from three city partners. In Section 7, we conclude the paper and lay down our future steps.

## 2. Literature Review

The aim of our literature review is threefold: 1) to examine the current state of the arts in terms of applications of maturity model, 2) to elaborate the contribution of maturity model applied for city resilience, and 3) the use of SD models, as a mean to convey insights and learn about resilience behaviors exposed by different models of policy structures and allow decision makers to select the optimal one. Eventually, we reveal the gaps in the current literature and the potential contributions of this work.

A maturity model is not a new concept, as it has been used among software industries to establish a road-map describing the maturity of a software in the 1990s [8]. Maturity models have their origin in the discipline of quality management. In 1979, Crosby [9] and Nolan [10] proposed independently of each other the concept of maturity stages as stepping stones on the path toward increasing process quality. Using a maturity model, an organization can measure the quality of their processes and improve them through maturity stages that build on each other.

The software industry quickly adopted maturity models such as the Capability Maturity Model (CMM) for software based on work by Humphrey [11, 12]. Over time CMM was extended to the Capability Maturity Model Integration (CMMI) intended as a framework “to solve any performance issue at any level of the organization in any industry” [13]. In the decades since their inception in 1979, maturity models have been applied in dozens research and disciplines.

How mature are maturity models themselves? Wendler [14] conducted a mapping study to answer this question and reviewed various definitions for maturity model. He adopted the definition by Becker et al. [15]: “A maturity model consists of a sequence of maturity levels for a class of objects. It represents an anticipated, desired, or typical evolution path of these objects shaped as discrete stages. Typically, these objects are organizations or processes.”

Wendler’s study investigates application domains of maturity model which covered publications until 2010 and finds that by 2010 maturity models had been applied in 22 domains [14, Fig. 13, p. 1328]. Wendler also looks at the validation of maturity models, particularly maturity models that satisfied the paradigm of design science [16], i.e. the utility, quality, and efficacy of a design artifact must be demonstrated via well-executed evaluation methods. Among the 108 studies on maturity models in Wendler’s mapping study, less than half (42) were design-oriented and, with one exception, all were validated. The validation methods employed were in about half of the instances cases study/action research, in about one-third surveys and the remainder were validated based on interviews/ discussions. To complete Wendler’s survey, we have conducted a literature study on the application domain of maturity model studies published since 2011 as shown in Table 1.

Table 1: Maturity Model in Literature

Application domain	Topic	Source
Software engineering	Agility	Gren, Torkar et al. [17]
Cybersecurity	Critical Infrastructure	Karabacak et al. [18]
Business intelligence	Application of data analytics in organizations	Lismont et al. [19]
	Implementation of electronic health records	Brooks et al. [20]
Engineering	Design automation	Willner et al. [21]
Electronic government	Open Government/ Social media	Lee et al. [22]
Energy management	Linking ISO 50001 processes and CMMI	Jovanović et al. [23]
Environmental management	Natural resource management/ Sustainability	Ngai et al. [24]
Manufacturing	Environmentally conscious design (eco-design)	Moultrie et al. [25]
	Industry 4.0	Schumacher et al. [26]
	Product development	Kandt et al. [27]
Safety	Supply chains	Mendes et al.
	Quantitative risk assessment	Rae et al. [28]

From the mapping study above we noticed that fully validated maturity model targeting city resilience, as a road-map to achieve a higher status of resilience has not yet been studied. And especially, how this will be implemented and manifested in more concrete policies and can be used by city stakeholders to define their future resilience strategies and action plan.

The RMM formulated in our SMR project has fulfilled this gap. The RMM was an outcome of the first 12 months of the project implementation through four workshops of intensive focus group discussions with city experts and stakeholders to gather various aspects of city resilience ranging from definitions, dimensions, policies, and indicators. Two-round Delphi process and one workshop were also carried out to validate the resilience components identified in this project.

The city RMM is a road-map presented as a table (See Fig. 1). It consists of 1) The main columns encompass five resilience maturity stages: Starting, Moderate, Advanced, Robust and vertebrate. There are set of policies defined under each maturity stage. 2) The table comprises four main rows representing resilience dimensions i.e. Leadership and Governance (**L**), Preparedness (**P**), Infrastructure and Resources (**I**), and Cooperation (**C**). Each dimension is split further into sub-dimensions. For example, **P** divided into two sub-dimensions: Diagnosis (**P1**) and Assessment (**P2**).

Dimensions	Subdimensions	Starting	Moderate	Advanced	Robust	Vertebrate
Leadership and governance ( <b>L</b> )	<b>L1</b> Municipality, cross sectorial and multi-governance collaboration	L1S1 L1S2	L1M1 L1M2 L1M3 L1M4 L1M5	L1A1 L1A2	L1R1	L1T1
	<b>L2</b> Legislation and development and refinement		L2M1	L2A1 L2A2		L2T1 L2T2
	<b>L3</b> Learning culture	L3S1	L3M1	L3A1	L3R1	L3T1 L3T2
	<b>L4</b> Resilience action plan	L4S1	L4M1	L4A1 L4A2	L4R1	
Preparedness ( <b>P</b> )	<b>P1</b> Diagnosis and Assessment	P1S1	.....	.....	.....	.....
	<b>P2</b> Education and Training	P2S1	.....	.....	.....	.....
Infrastructures and Resources ( <b>I</b> )	<b>I1</b> Reliability of Cis and their interdependencies	.....	.....	.....	.....	.....
	<b>I2</b> Resources to build up resilience and to response	.....	.....	.....	.....	.....
Cooperation ( <b>C</b> )	<b>C1</b> Development of partnerships with city stakeholders	.....	.....	.....	.....	.....
	<b>C2</b> Involvement in resilience networks of cities	.....	.....	.....	.....	.....

Figure 1: Illustration of the structure of the RMM Road-map

The Resilience Maturity road-map also defines the stakeholder involvement in each resilient maturity stage. Currently, we have identified and validated 98 policies for all maturity stages in different SMR workshops. To recognize which policy belongs to which dimension and which maturity stage, a coding system has been developed for each policy. For example, **P1S1** means that a certain policy belongs to the first sub-dimension of Preparedness (P1), and the first policy at the Starting stage. The examples of concrete policies are given in Section 4.2.

Amongst several computer simulation modeling approaches, merely SD engages its model users by showing them the underlying system structure. SD shows its model users how their policies and decision affect the end results over time, in terms of patterns, trends, and aggregate values, which in turn supports

planning and strategic level decisions. Moreover, SD has fewer requirements when it comes to its model users' skill sets, which enables them to participate in building in addition to using the models [29].

A key purpose of a SD model is policy modelling and testing [4]. Nonetheless, to what extent is this applied in the field of city resilience? We find several publications which followed a qualitative SD approach by developing Causal Loop Diagrams. Armendáriz et al. in [30] depict the Causal Loop Diagram aiming at finding ways to enhance food systems' resilience and sustainability. In [31, 32], Causal Loop Diagrams were used in tackling the issue of the environmental effect of production, especially on enhancing sustainability and resilience of organizations and societies by redistributing manufacturing. Causal Loop Diagram was used by [33] to model the social vulnerability and resilience when implementing climate change adaptation policies.

Several other publications combine SD with Geographical Information Systems to analyze urban resilience in the face of coastal hazards resulting from climate change such as Simonovic and Peck's work [34, 35]. Their generic model is considered to be the first quantitative model representing resilience temporally and spatially [36]. It was used as basis for many others publications, for example, Gotangco et al. [37] to investigate household and local government assets resilience in the face of flooding hazards.

In our case we are more interested in the overall effect of implementing the resilience policies, particularly in the order prescribed by the RMM. Yet, the resilience level estimation is to be taken into consideration in terms of the indicators of the RMM's four dimensions. The specific details of the policies are not as important as the overall picture; accordingly, it is convenient to model these policies on the abstract level without diving into their details.

### 3. Model Requirement and Boundary

Recall that this paper is the first effort to find the mechanics of the SD model that can show the policy interactions and allow users learning on the SMART sequence of the RMM. The workshops and model feedback were partly described by Iturriza [38], and here, we only reveal the technical implementation of the policy modeling. In brief, the purpose of the SD model is to use it as a tool for training the city stakeholders on prioritizing the policies according to the SMART trajectory, simulating various policy sequences and budget allocations to achieve higher levels of resilience efficiently. Several high-level requirements of the model emerged from the SMR workshops are defined below.

- The model can simulate the resilience policies and capture the interdependencies between them.

- The model can show the evolution from one SMART resilience stage to another (higher) stage.
- The model should represent all dimensions and sub-dimensions, including the selection of policies of each sub-dimension.
- The model should consider the indicators defined for the RMM dimensions to measure the impacts of the different sequences of policies implementation.
- The model allows external inputs and can be used for step-by-step simulation. It allows the model to revise their future decisions and set the approximate implementation of each resilience policy.

The policies included in the model are limited to only 19 policies instead of 98 policies. The time horizon for the model is 60 months.

## 4. Policy Structure and Model Description

### 4.1. Design Overview

One of the main issues addressed in this paper is how to model the policy structures and dependency between individual policies to allow users making optimal decisions in implementing resilience policies. We consider two scenarios of the policy modeling to achieve this goal. The models are simple, yet have some details, especially in describing the connection between different policy implementations at different maturity levels of resilience as follow:

1) **Policy Structure 1:** It illustrates a case where the implementing of a new policy requires its predecessor policies have passed certain implementation level threshold, before seeing the impacts on resilience dimensional indicators.

2) **Policy Structure 2:** It illustrates a case where the connection between successive policies solely affects the indicators' values. In this case, the dependency between these policies **will not prevent** a city from starting new policies. Nonetheless, if the correct sequence of implementing the policies was ignored, the consequences will be reflected in the value of the indicators.

### 4.2. System Dynamics Model Description

An SD model is typically represented diagrammatically through sets of stocks and flows. A stock is depicted as a rectangle, representing a state variable or accumulation of material, which can increase or decrease depending upon the inflow to or outflow from the stocks. The flow is depicted as a valve that determines accumulation in the stock. In SD, both informational and non-informational entities can move through flows and accumulate in stocks.

To experiment with the two policy structure scenarios, we built a SD model consists of three sub-models: 1) The policy implementation, 2) Policy implementation costs, and 3) SMART indicators. The

stock and flow diagrams of the policy implementation of the RMM will be presented in the next sections. For simulation purpose, mathematical equations need to be embedded into the model. The model description includes the corresponding equations as seen in Table 2.

Table 2: Mathematical notations used in the model

Notation	Meaning	
<b>Represented in Fig. 3</b>		
$IR_{i+1}$	Implementation Rate of the next policy $i$	L1M2 Implementation Rate
$IL_i$	Implementation Level of policy $i$	L1S2 Implementation Level
$ILt$	Implementation Level Threshold of policy $i$	L1S2 Implementation Level Threshold
$EfBE$	Effect of Budget on Expenditure	Effect of Budget on Expenditure
$IL_{i+1}G$	Implementation Level Goal of next policy $i$	L1M2 Implementation Level Goal
$IL_{i+1}$	Implementation Level of next policy $i$	L1M2 Implementation Level
$I_{i+1}t$	Implementation time of next policy $i$	L1M2 Implementation Required Time
<b>Represented in Fig. 4</b>		
$EIL_{i+1}$	Effective Implementation Level of next policy $i$	L1M2 Effective Implementation Level
$EIL_i$	Effective Implementation Level of policy $i$	L1S2 Effective Implementation Level
$ILt$	Implementation Level Threshold of policy $i$	L1S2 Implementation Level Threshold
$IL_{i+1}$	Implementation Level of next policy $i$	L1M2 Implementation Level
<b>Represented in Fig. 6</b>		
$AB_t$	Available budget at time $t_i$	Available Budget
$AB_{init}$	Initial available budget	Initial Available Budget
$UB_i$	Used Budget of a policy	L1S2 and L1M2 Used Budget
$SP_t$	Spent budget at time $t$	Spent Budget

#### 4.2.1 The Policy Implementation Level Sub-Model.

Before explaining the model any further, an illustration of the policies under the *Leadership and Governance (L)* dimension is provided in Table 3.

Table 3: Example of policies

<b>Dimension: Leadership and Governance, Sub-Dimension 1: Municipality, cross-sectorial and multi-governance collaboration</b>	
<b>S</b>	<b>(L1S2)</b> Incorporate resilience into visions, policies and strategies for city development plans
<b>M</b>	<b>(L1M1)</b> Establish a resilience department or committee and a cross departmental coordination board and procedures
<b>A</b>	<b>(L1A1)</b> Align, integrate and connect the resilience action plan with national plans
<b>R</b>	<b>(L1R1)</b> Align, integrate and connect the city resilience plan with regional, national and international resilience management guidelines
<b>T</b>	Not included

And under the sub-dimension 1, **L1** (Municipality, cross-sectorial, and multi-governance collaboration),

there are four policies included in our model, specifically **L1S2**, **L1M1**, **L1A1**, and **L1R1**. For illustration, the links between these four policies can be simplified as shown in the diagram in Fig. 2.

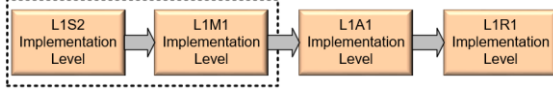


Figure 2: The links between policies in L1

To demonstrate how the SMART policy implementation process is modeled, we describe only the **L1S1** and **L1M1** structure (inside the dashed-line box in Fig. 2). Generally, the interactions between the same dimension's policies in the model are similar. Yet, the number of policy links are different from dimension to another depending upon the sequences of policies in the RMM, as shown earlier in Fig.1.

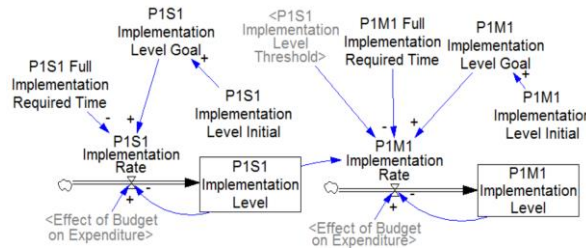


Figure 3: Policy Implementation Level Structure 1

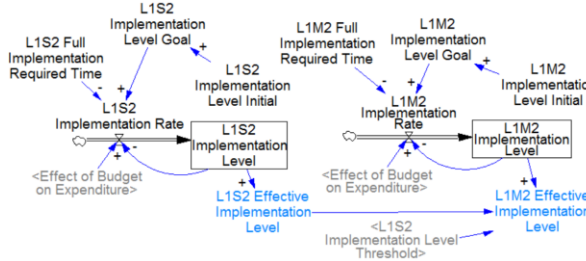


Figure 4: Policy Implementation Level Structure 2

The model presented in Fig. 3 shows the transformation of the two examples of policy interactions in Fig. 2 into the stock-and-flow diagram. The *policy implementations levels*, i.e. **L1S2** and **L1M2** are modeled as stocks. The inflow to the stock of each policy comes from the *implementation rate*. The link between the two policies indicates that when the implementation level of **L1S2** exceeds the threshold, the next relevant policy in sequence **L1M1** can be carried out, i.e. the information about implementation level of a specific policy will influence the implementation of the next policy in a higher maturity level. The policies are modeled and structured in line with the sequences of policies in the SMART table (recall Fig.1).

The existence of two implementation rates in Fig. 3 should be noticed. At the starting stage, only four variables affect the implementation rates, i.e. *Full Implementation Required Time*, *Implementation Level Goal*, *Implementation Level*, and *Effect of Budget on Expenditure*. Nevertheless, in the higher maturity level, the previous policy *Implementation Level* and *Implementation Level Threshold* of **L1S2** affects the subsequent policy *Implementation Level*, i.e. **L1M2**.

The link between the policies and the policy implementation structure is repeated for all policies under the same sub-dimension. The rate is a critical point that controls the behavior of the model. We define the equation for the rate as in Equation 1-A.

$$IR_{i+1} = \text{if then else} \left( IL_i > ILt, \right. \\ \left. EfBE \times MAX \left( \frac{IL_{i+1}G - IL_{i+1}}{I_{i+1}t}, 0 \right) \right) \quad \text{Equation (1-A)}$$

The MAX function ensures that the stock value of **L1M2 Implementation Level** does not fall below zero. While the information about the implementation of the previous policy **L1S1** will only affect the efficiency of the next policy implementation i.e. **L1M2** when the progress exceeds a certain threshold (represented by the *Implementation Level Threshold*). Meanwhile, as captured by the *Effect of Budget on Expenditure* variable, the budget affects the policy implementation rate as well.

The *if-then-else* function is a logical function that governs whether the next policy can be implemented or not. Its value depends on two factors: 1) budget availability, and 2) the implementation progress of the previous policy exceeding its threshold.

The two parameters called **L1S2** and **L1M1 Implementation Level Initial** are “interface” for later use where the model user can decide or assess the progress of a particular policy at the beginning of the simulation. This is modeled as a percentage, where zero percent indicates that the policy is not yet at all in place, while 100% means that the policy is fully implemented.

Fig.4 shows the alternative policy structure 2, where we repeat the structure in Fig. 3, except that the *Implementation Rate* is not affected by the previous policy anymore. The rationale behind this change is to give the model user the freedom to spend budget and implement policies out of the RMM order. Two additional auxiliary variables are shown in Fig.4, namely **L1S2** and **L1M2 Effective Implementation Levels** (marked with blue text). The *Policy Effective Implementation Levels* will be considered in calculating the dimensional indicators as will be



shown in later subsections of this paper. We define the *Effective Implementation Level* as follows:

$$EIL_{i+1} = \text{if then else } (EIL_i > IL_t, \quad IL_{i+1} \times , 0) \quad \text{Equation (1-B)}$$

**4.2.2. The Policy Cost Sub-Model.** The model includes a budget constraint (available budget) which will be allocated by the model user to the implementation of different policies. Each policy has a cost. Consequently, once the model user defines a budget goal for a selected policy, the budget available will deplete with the same amount. The intention this sub-model is to trace the budget allocation (available, used budget, and total budget that has been used). Their relationship can be seen in Fig. 5.

For convenience, instead of showing all 19 outflows, we only portray two outflows from *Available Budget* spend on the **L1S2** and **L1M2** policies—the same example as we used for the *Policy Implementation Sub Model*. The *Available Budget* is modeled as a stock. It has 19 outflows connected to the *Used Budget* stock of each policy, through rates called *Spending on L1M2*, *Spending on L1S2*, etc.

In this sub-model, the used budget from each policy will increase the *Spent Budget*. This variable is intended for the calculation purpose, as it is the model user's information source to track and monitor remaining budget available after spending money to implement different policies.

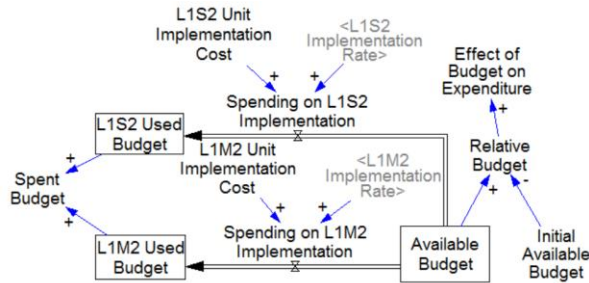


Figure 5: Available, Spent, and Used Budget

To explain this model, let us consider that  $AB$  is the available budget, and  $UB_1, UB_2 \dots UB_n$  are the budget values allocated to the different policies, or represent them with the general term  $UB_i$  that denotes the budget allocated to the  $i^{\text{th}}$  policy. As  $AB$  denotes a stock, it is expressed by the following equation:

$$AB_t = \int_0^T (AB_{init} - UB_i)_t dt \quad \text{Equation (2)}$$

On the other side, the Spent Budget  $SP$  is the summation of money allocated in  $UB_i$  which can be expressed as follows:

$$SP_t = \left( \sum_{i=1}^n UB_i \right)_t \quad \text{Equation (3)}$$

**4.2.3. The SMART Indicator Sub Model.** In line with our endeavor to test the two policy structures, we show the main difference occurs in the Indicator sub model of these two structures in Fig. 6. In this section, we focus on the *Leadership and Governance Indicator*, and the first sub-dimension indicators depicted as *L1 indicator* weight as an example.

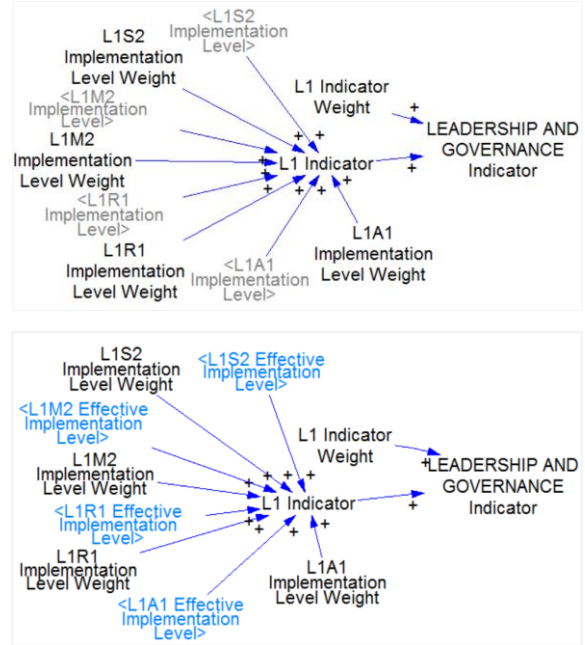


Figure 6: Indicator Sub Model with L1 Indicator as an Example (design 1 on the top and design 2 on the bottom)

Let us consider  $ILW$  that represents the *Implementation Level Weight* of all policies and  $IL$  that captures the *Implementation Level* (See sub-model Policy Implementation). As the model contains weights from multiple Policy Implementations ( $IL_1, IL_2, \dots IL_n$ ), we can state that the *Implementation Level Weight* variable consists of a set of weights of different policy implementations ( $ILW_1, ILW_2, \dots ILW_n$ ). As we are interested in calculating the indicators at the sub-dimension level, we model it in Fig. 6 as *L1 Indicator* and only relevant policy under L1 indicator that is considered in the calculation.

$$L1I = \sum_{i=1}^n (IL1W_i * IL1_i) \quad \text{Equation PS 1 (4-A)} \quad L1I = \sum_{i=1}^n (IL1W_i * EIL1_i) \quad \text{Equation PS 2 (4-B)}$$

In the second policy structure, instead of using the *Policy Implementation Level* in calculating the sub-dimension indicators, we use the *Policy Effective*

*Implementation Levels* ( $EIL_1, EIL_2, \dots, EIL_n$ ) as seen in Equation PS 2.

To calculate the values of the Indicators, we need to decide a weight for every policy contributing to the value of this indicator. It would have been straight forward to give all the five stages the same weight of 0.2. However, there are stages that contain no policies. In such a case, the empty stage weight is summed to the weight of the next stage.

Furthermore, the number of policies in each stage and dimension is not the same. This makes calculating weights for individual policies challenging. We need these weights to generate an indicator that shows the current stage in addition to showing progress inside this stage in terms of individual policies' implementation levels. With our selected 19 policies, the **Leadership indicator**, as an example, should indicate that the city is in the **M (Mature)** stage if they have finished implementing **L1M2**. However, if they are in the **A (Advanced)** stage, the indicator should have smaller weights for policies in this stage as they are four instead of one as in the previous stage. Yet, the indicator should take the individual policies implementation level as progress within the stage.

Finally, if we took sub-dimensional indicators to be  $LS_1, LS_2 \dots LS_n$  and their corresponding weights  $LSW_1, LSW_2 \dots LSW_n$  (which there was no reason not to keep them equal to the unity in this version). Then, the calculation for *Leadership and Governance Indicator* of the policy implementation can be stated as follows:

$$LGI = \sum_{i=1}^n (LSW_i * LS_i)$$

Equation (5)

## 5. Testing Two Policy Structures

This section examines the advantages-disadvantages of two modelling possibilities as described in section 3 and 4. The model that give better advantages for learning purpose is then used as a basis for testing in Section 6 and future SD RMM development. The analysis focuses on observing the different behavior of the model due to variations of implementation of dependencies between policies as explained in Section 3. To clarify both cases and the difference, let's consider the following use case. A model user has a certain amount of budget and has to allocate the budget for implementing resilience policies and considering the correct policy sequence. This model user can revise her/his decisions every three months on the policy priority.

We compare the simulation behaviors of our two policy structures from one time step to another. We tested four interventions where the model user can change decisions every three months from month 0 to

month 12. In these tests, we intentionally implemented policies out of the correct order so that we can detect the potential learning expected from the model.

In the *first intervention* at time  $t=0$ , we set a goal of 100% implementation level for the policy **L1A1**, tested with both *Policy structure 1* and 2. In the *second intervention* at  $t=3$ : the goal for implementation level of the next policy **L1M2** was set to 100%, leaves everything else as it is. In the *third intervention* at  $t=6$ , we set the goal for implementation level of policy **L1S2** to 100%. In the *fourth intervention*: we left the goal for implementation levels of the three policies as is.

The testing results are presented in the Fig. 7 (the development of the Leadership and Governance indicator over time) and Table 4 (The Progress of Policy Implementation Level). In Fig. 7, *Policy structure 1* is captured by a blue solid line while *Policy structure 2* is represented by a dashed line. Four vertical dashed lines in the chart area represent the phase of intervention described earlier. Table 4 summarizes and compares the simulation results concerning the implementation levels of the two policy structures (PS1) and (PS2).

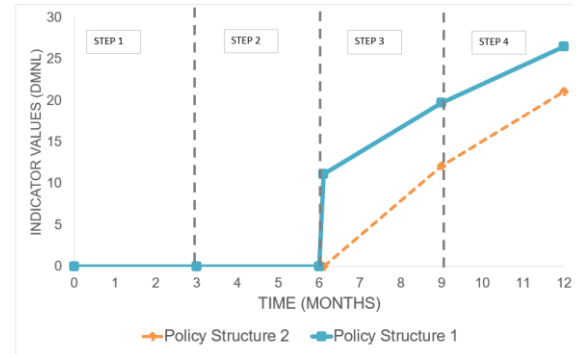


Figure 7: Testing Results of Policy Structure 1 and 2

Table 4: The Progress of Policy Implementation Level

	Intervention							
	First		Second		Third		Fourth	
	PS1	PS2	PS1	PS2	PS1	PS2	PS1	PS2
<b>L1S2</b>	0%	0%	0%	0%	0%	0%	28%	28%
<b>L1M2</b>	0%	0%	0%	0%	0%	28%	27%	49%
<b>L1A1</b>	0%	0%	0%	29%	0%	49%	26%	63%

The behavior comparisons from time step to time step can be explained as follows: **After 3 months:** With *policy structure 1*, the system will not allow spending budget on implementing **L1A1** and accordingly the implementation level of this policy will stay at 0. While with *policy structure 2*, the system will start spending the budget on implementing **L1A1** and accordingly, the implementation level of this policy will start increasing. In both models, the Leadership and Governance indicator value will stay at 0. The reason of these behaviors is that the decision maker did not follow the correct sequence of policy implementation.

**After 6 months:** in *policy structure 1*, the system will neither allow spending budget on implementing **L1M2** nor **L1A1**, and accordingly the implementation level of the both policies will stay at 0. Consequently, the Leadership and Governance indicator value will stay at 0 as well. With *policy structure 2*, the system starts spending the budget on implementing **L1M2**, continues spending on **L1A1**, and accordingly the implementation level of **L1M2** will start increasing and continues to increase for **L1A1**. However, the Leadership and Governance indicator value will stay at 0.

**After 9 months:** with *policy structure 1*, The system will start spending the budget on implementing **L1S2**, **L1M2** and **L1A1**, and accordingly the implementation levels of the 3 policies will start increasing concurrently. Consequently, the Leadership and Governance indicator value will start increasing as well. While with *policy structure 2*, the system will start spending the budget on implementing **L1S2**, continues spending on **L1M2** and **L1A1**, and accordingly the implementation levels of **L1S2** will start increasing and continue to increase for the other 2 policies. Consequently, the Leadership and Governance indicator value will suddenly increase by the starting implementation value of **L1S2** and the already improved values of implementation of **L1M2** and **L1A1**.

**After 12 months:** with *policy structure 1*, The three policies implementation levels continue to progress concurrently with the same rate. While with *policy structure 2*, the three policies implementation levels continue to progress concurrently with different rates directly proportional to when each policy implementation started. Meanwhile, the Leadership and Governance indicator values in both policy structures continue to increase.

Based on the results of the above-mentioned experiments, the table below summarizes the lessons learned from our model testing regarding advantages (A) and disadvantages (D) of two policy structures.

*Policy structure 2* gives the user a more realistic experience. The user can spend incorrectly, and learns from this, while design 1 prevents this type of mistakes. The issue of sudden changes in the indicators time behavior in *policy structure 2* can be rectified via an appropriate smoothing structure. In general, a city can decide to start implementing certain policy out of sequence. They will spend the money on this policy implementation; however, it will not give the required effect until the previous policies are implemented.

Nonetheless, we cannot ignore that in reality it might be true that cities cannot start implementing certain policies before the previous ones for practical reasons in certain cases. Although it is not the case with any of selected policies in our model, it is possibly the case with some of the rest policies.

Table 5: Advantages (A) and Disadvantages (D) of two Policy Structures

	Policy Structure 1	Policy Structure 2
<b>A</b>	The indicators time behavior will be smooth all the time.	The user gets the opportunity to make mistakes by spending incorrectly, and not seeing any results.
<b>D</b>	The user cannot spend incorrectly.	The indicators time behavior suffers sudden changes.

Clearly, a hybrid approach of *policy structure 1* and 2 based on the nature of every policy is the optimal general solution. Otherwise, for educational purposes, *policy structure 2* becomes more attractive for providing a better learning opportunity. To sum up, in this Section 5 the whole experiments are intended for testing two policy structures in the model and observe our hypothesized behaviors of the resilience dimensional indicators. In the next section, we simulate the two models using the actual parameters of three city partners that will participate in pilot tests of the SD resilience model, i.e. Donostia/San Sebastián (Spain), Glasgow (UK) and Kristiansand (Norway).

## 6. Model Experiments

The aim of this section is to show multiple application of the model into different cases to show the model capability to be applied into different cities. According to the project partner cities' self-evaluation, Donostia/San Sebastián (Spain) is between the **Starting** and the **Moderate** stages, Glasgow (UK) is in the **Advanced** stage, while Kristiansand (Norway) is in the **Robust** stage. Data for policies implementation costs and required time was collected from these cities in one of the project workshops in Donostia/San Sebastián in March 2017. In case any data item was missing, it was replaced by the average value, except for Kristiansand, for which there was an additional dataset collected beyond the workshop. The model is encapsulated in user-friendly Interactive Learning Environment, which were described in Ituriza [38], and is the basis for implementing the experiments in this section. There are sets of parameters that can be changed by a user, as we did to test and simulate the scenarios below.

Three simulation scenarios were conducted and presented in Fig. 8: 1) Implementing all policies at the beginning of the simulation, 2) Implementing policies in their SMART sequence, and 3) Implementing policies based on random sequence (the same sequence for the three cities). In general implementing all policies at the beginning gives the highest results on the dimensions indicators. However this is neither economical or realistic. On the other hand, implementing policies according to the SMART sequence gives almost the same results, yet more economical and realistic. Going out of sequence gives the worst results in all three cities (red dotted lines).



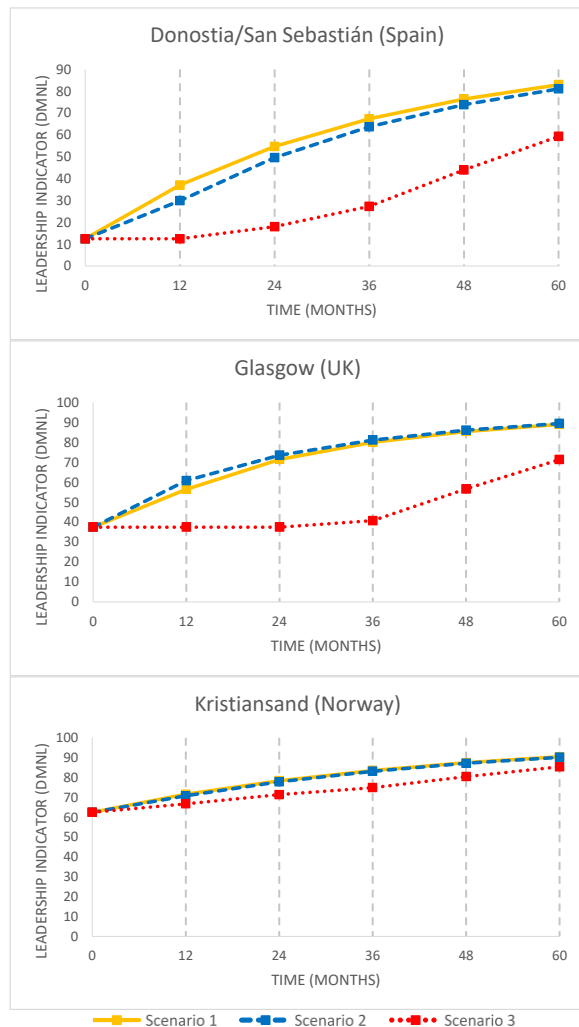


Figure 8. Simulation Results of three cities: Donostia/San Sebastián (top), Glasgow (middle) and Kristiansand (bottom)

## 7. Conclusions and Next Steps

In its simplest design, the model has worked as desired and provides the expected behaviors, in terms of its capability to show and play with policy order. If the user does not implement a policy according to the correct order, then the budget will be used up but the expected resilience indicator enhancement will not be achieved. We also have identified the advantages and disadvantages of using two different policy structures. With policy structure 1, the indicators time behavior will be smooth all the time, which is graphically nice, but the user cannot spend incorrectly, which is actually a disadvantage from a learning perspective. On the contrary, with policy structure 2, the model user gets the opportunity to make mistakes by spending incorrectly, by not seeing any indicator enhancements when simulating in an incorrect sequence. The disadvantage is that the indicators time behavior suffers sudden changes.

The model presented in this paper covers 19 policies (20% of total policies have been defined in the actual RMM). For these 19 policies, policy structure 2 is realistic, as there is no reason that prevents model users from implementing these policies out of sequence in real life. Yet, we admit that for many other policies that are not included, policy structure 1 could be more realistic, as for them it will be impossible to be implemented without implementing their predecessor policies. Accordingly, for a more comprehensive SD model that includes all 98 policies –which is out of our training purposes model– both policy structures should be considered based on every policy case individually.

As the SD model building process is iterative by its nature and engages stakeholders from the city project participants, a set of validation plans have been laid out, both for the sake of the SD model itself, and for a needed Graphical User Interface as well. Part of the future research will include the strategy on how the cities can use the model so that it is a useful tool to teach them to prioritize and adopt resilience policies in a right order and can bring city resilience level from Start to Robust, or even VerTebrate. The city stakeholders can discuss their current and future policies, analyze which policies need to be prioritized and simulate their decisions in iterative manner.

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